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Chapter

Challenges of Biochar Usages in Arid Soils: A Case Study in the Kingdom of Saudi Arabia

Khalid A. Alaboudi

Abstract

Biochar is a carbon-rich material produced from the pyrolysis of organic biomasses in the absence of oxygen or under low-oxygen conditions. Biochar has received a great interest during the last few decades due to its beneficial roles for carbon dioxide capturing and soil fertility improvement. However, applications of biochar in arid soils are very limited, and there is a lack of knowledge on practical aspects of adding biochar to arid soils. In this chapter, we will focus on biochar applications in the Kingdom of Saudi Arabia soils as an example of arid soils. These soils are characterized by several marks, i.e., high soil pH, sand structures, high $CaCO_3$ contents, and low soil fertility. In addition, the unsuccessful recycling practices of agricultural and food wastes in the Kingdom of Saudi Arabia are also discussed. This chapter provides an overview of current biochar knowledge pertinent to its application to arid soils, summarizes what is known so far about biochar and its applications in arid regions, and demonstrates the possible strategies that can be used for enhancing the practices of biochar addition to these soils.

Keywords: biochar, carbon sequestration, soil fertility, applications, limitations

1. Introduction

Soil formation is a complex process resulting from long-term interactions among several environmental factors, i.e., climate, soil-forming processes, and land uses [1]. Such processes influence soil's physical, chemical, and biological characteristics and hence affect soil productivity [2]. In arid and semiarid regions, many challenges may face soil productivity; for example, many arid soils are of light texture with low organic matter and nutrient contents [3–5]. These soils exhibit low soil aggregation and can, therefore, be subjected easily to wind erosion [6]. Moreover, secondary minerals may dominate in such soils like calcite and gypsum [1], and these minerals can significantly diminish soil fertility [7, 8]. Another important threat that faces agricultural sustainability in arid sand semiarid soils is soil salinity [9]. Generally, the term arid or semiarid refers to the regions of limited rainfall and high evapotranspiration [10]. Areas with mean annual precipitation (MAP) ranging from 100 to 250 mm yr^{-1} are called arid climatic zones, while areas with MAP ranging between 250 and 600 mm yr^{-1} are called semiarid zones [11]. These two climatic regions cover approximately 30% or more of the total earth's surface [12]. To improve the productivity of low-fertility soils, organic applications should therefore be incorporated within the top soil [13, 14] to raise soil contents of both C and nutrients [14]. However, the negative implications of using easily decomposed organic amendments on the environment should be taken into account, e.g., emissions of greenhouse that possesses global warming [15]. Accordingly, biochar might be the appropriate organic amendments to improve the characteristics of such soils but decrease the emissions of greenhouse gases on the other hand. In the following section, we will discuss the distribution of arid and semiarid soil and the potentialities of using biochar to improve soil properties and attain sustainability in crop production

2. Distribution pattern of arid and semiarid soils

As shown in **Figure 1**, arid and semiarid soils are located in North and South Africa, the Middle East region, North and South America, and finally in Australia [16]. More than 95% of the total arid soils exist in Africa and Middle East regions. According to the UNEP [16], aridity index (AI) is commonly used to quantify the aridity of a specific region. Briefly, this index is estimated based on climate variability by calculating the ratio of annual average rainfall to potential evapotranspiration (P/PET). For this concern, lands are classified in the following ascending order based on the average precipitation: hyperarid, arid, semiarid, and dry subhumid, and their average precipitation rates are 0, 1–59, 60–119, and 120–179 mm yr^{-1}, respectively [16]. In this chapter we will focus on the Kingdom of Saudi Arabia lands as an example of arid lands and the major problems hindering the application of biochar technology in these soils. In the Kingdom of Saudi Arabia, almost 25% of the total land area is arable lands (52.7 million ha), in which 45% are calcareous, sandy textured soils, with very low contents of organic matter and nutrients [17].

3. Major characteristics of arid soils

Salt content, in many arid soils, is relatively high. These soils accumulate on the soil's surface because of the high evapotranspiration rates. In addition, these regions have dry climate with high temperature and high evaporation rate. The

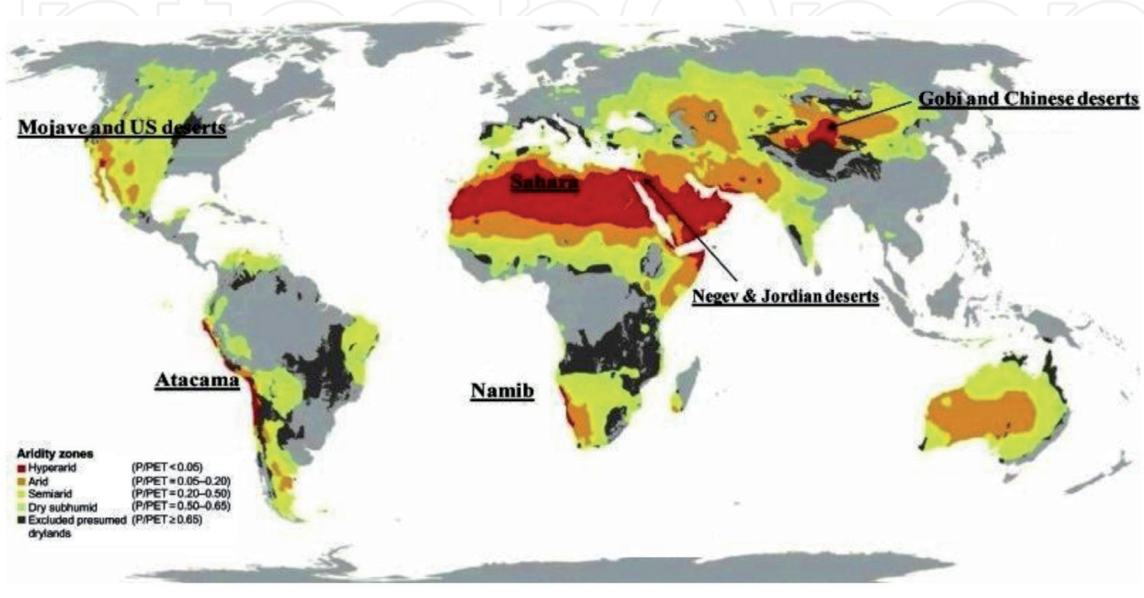

Figure 1.
Distribution pattern of arid and semiarid regions [16].

deeper soil layers are usually occupied by Ca. The arid soils can be applicable for cultivation in case proper water for irrigation becomes available. Due to high temperature, the degradation rate of soil's organic matter in arid soils is very high; consequently, these soils need further application rates. In the Kingdom of Saudi Arabia, most of agricultural soils are of coarse texture, with high $CaCO_3$ contents and high pH values. The lack of sufficient water in the Kingdom of Saudi Arabia led to increase the potentiality of soil salinization. Therefore, these soils are of poor fertility, in terms of physical (high infiltration rate, sand texture, and bad hydraulic properties), chemical (low organic matter contents, insufficient nutrients, and high soil pH), and biological (low microbial communities in soils due to the absence of organic residues and soil nutrients) characteristics [18]. Usually the pH value in the Kingdom of Saudi Arabia soils is greater than 8 with high $CaCO_3$ contents (>30%) [19]. In spite of the Kingdom of Saudi Arabia having the largest land mass among Middle East countries, it has the lowest arable land per capita worldwide [20]. A point to note is that the major water sources in the Kingdom of Saudi Arabia are groundwater and desalination of seawater [21]. Therefore, intensive studies are performed to overcome the infertility problems of arid soils in the Kingdom of Saudi Arabia by using organic and inorganic soil amendments, i.e., compost bio inoculums and mineral polymers [22–24]. However, these amendments need to be applied intensively because of their low nutritive contents and fast degradation rates [25].

4. Agricultural and food wastes in the Kingdom of Saudi Arabia

Due to the arid characteristics of Kingdom of Saudi Arabia lands, agricultural activities are also thought to be very low. According to the World Bank [20], the agricultural lands in the Kingdom of Saudi Arabia cover only 1736.472 km^2 [20]. On the other hand, the Kingdom of Saudi Arabia is considered the largest food and agricultural importer in the Gulf Cooperation Council with average imported food products of 80% in 2013 [26, 27]. These conditions hinder the development of the agricultural sector in the Kingdom of Saudi Arabia. A positive point to note is that such arid conditions are suitable for cultivation of date palm plant. According to the Food and Agricultural Organization (FAO), the Kingdom of Saudi Arabia has the highest harvested areas of date palm in 2016 with an average area of 145,516 ha. Palm trees generate huge wastes annually [28]; accordingly, proper recycling and management of these wastes can improve soil conditions.

5. Biochar

Biochar is an organic carbon-rich product, produced by burning agricultural and animal wastes in the absence of oxygen [29]. Several studies demonstrated its beneficial role for improving soil fertility and waste management, remediation of contaminated soils and water, and reducing greenhouse gas emissions [25, 30, 31]. In this chapter, we will discuss the potential benefits of biochar as a soil amendment for improving its fertility and productivity.

5.1 Ancient production of biochar

Biochar was initially produced by ancient Egyptians to produce liquid wood tar from charring processes in order to cover and preserve the dead bodies [32]. Thereafter, in South America (terra preta), 2500 years later, biochar is created both

Feedstock	Temperature	pH	%							CEC, cmolc kg^{-1}	C/N ratio	%		H/C ratio	O/C ratio	SSA, $m^2 g^{-1}$	Reference
			C	N	P	S	Ca	Mg	K			O.M	Ash				
Sugar cane bagasse	<500	8.63	74.02	1.00	0.24	—	0.17	0.32	2.00	69.62	74.02	87.80	12.21	0.42	0.23	92.30	[31]
Orange peel	<500	8.75	66.36	2.13	0.25	—	1.04	0.28	1.86	68.28	31.15	88.80	11.17	0.65	0.32	0.20	
Oak wood	600.00	6.38	87.50	0.20	—	—	—	—	—	75.70	489.00	—	0.01	0.33	0.07	642.00	[40]
Corn stover	350.00	9.39	60.40	1.20	—	—	—	—	—	419.30	51.00	—	11.40	0.75	0.29	293.00	[41]
	600.00	9.42	70.60	1.07	—	—	—	—	—	252.10	66.00	—	16.70	0.39	0.10	527.00	
Corn stalk	400.00	9.60	51.10	1.34	0.25	—	—	—	1.34	—	38.13	—	—	—	—	—	[42]
	500.00	10.10	48.40	0.55	0.44	—	—	—	2.65	—	88.00	—	—	—	—	—	
Wheat straw	425.00	10.40	46.70	0.59	—	—	1.00	0.60	2.60	—	79.15	—	20.80	—	—	—	[43]
Rice straw	400.00	—	71.30	1.46	—	—	—	—	24.60	—	48.84	—	36.20	—	—	—	[44]
Peanut hull	500.00	8.60	82.00	2.70	0.30	0.10	—	—	—	—	30.37	—	9.30	0.44	0.03	200.00	[45]
Coco peat	500.00	10.30	84.40	1.02	0.03	0.27	0.06	2.30	—	—	82.75	—	15.90	0.41	0.10	13.70	[46]
Coconut charcoal	<500	8.86	76.50	0.20	—	—	—	—	—	—	426.60	—	2.90	0.12	—	—	[47]
Pinewood	<500	8.47	53.20	0.40	—	—	—	—	—	—	143.40	—	65.70	0.35	—	—	
Eucalyptus deglupta	350.00	7.00	82.40	0.57	0.06	0.03	—	—	—	4.69	144.56	—	0.20	—	0.12		[48]
Hardwood sawdust	500.00	—	63.80	0.22	—	0.01	—	—	—		290.00	—	22.80	0.60	0.14	1.00	[49]
Chinese pine	600.00	8.38	66.67	2.21	—	—	—	—	—	31.58	30.17	—	12.50	0.58	0.31	—	[50]

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Feedstock	Temperature	pH	%							CEC, cmolc kg^{-1}	C/N ratio	%		H/C ratio	O/C ratio	SSA, m^2 g^{-1}	Reference
			C	N	P	S	Ca	Mg	K			O.M	Ash				
Cattle waste	380.00	8.20	62.10	0.10	—	—	—	—	—	39.00	621.00	—	25.60	1.90	0.27	—	[51]
Sewage sludge	380.00	8.50	38.30	5.20	—	—	—	—	—	0.50	7.37	—	44.90	0.94	0.25	—	

Data obtained from Abdelhafez et al. [25].

Table 1.
Physicochemical characteristics of different types of biochar.

naturally by forest fires and by humans through burning bits for different practices, i.e., cooking and manufacturing [25]. In terra preta soils, the acidic conditions were the limiting factors affecting negatively crop production wherein these soils suffer severely from Al toxicity. To overcome this problem, the liming effect of biochar was an effective approach to overcome Al toxicity in soil [33].

5.2 Production technologies of biochar

All organic materials (feedstock, crop wastes, animal wastes manure) can be used for biochar production. Simply, biochar is a charcoal-like material that is produced in the absence of oxygen or limited oxygen conditions [25]. In this process organic wastes are burned at relatively low temperature < 700°C, and three main components are produced through the pyrolysis process, i.e., solid biochar (carbonized biomass with average C contents of >60), synthetic gas (which can be used as a power source), and bio oil (fuel material) [25]. Farmers in the past used to burn the agricultural wastes under limited oxygen conditions by covering the waste piles with soil dust. In this traditional method, approximately half the amount of organic C was lost into the atmosphere. Therefore, people have tried to develop the production technology through using pit kiln and brick kilns in order to eliminate the losses of C and other gas emission. After biochar technology has risen, non in situ equipment have been designed to maximize the biochar yield, eliminate the C lose and ash content and using syngas and bio oil as secondary products [25]. It is worthy to mention that organic materials start to decompose at low temperature (about 120°C), followed by hemicellulose and lignin compounds, which degrade at 200–260°C and 240–350°C, respectively [34].

5.3 Physical and chemical characteristics of biochar

Both pyrolysis conditions and the types of organic wastes identify the major characteristics of the produced biochar [25, 35]. Usually biochar (a carbon-rich product) is characterized by its high surface area and lower concentrations of hydrogen and oxygen [36, 37]. Thus, its application can improve soil characteristics (chemical, physical, and biological). Moreover, this organic product is considered relatively stable in soil because of its low availability of labile organic carbon [38] besides its low content of nutrients [39]. **Table 1** shows the main physiochemical characteristics of different types of biochars. For both physical and chemical characteristics, pyrolysis conditions and type of organic wastes are the main factors identifying them. Clearly, all biochars have the same characteristics, especially the high C contents and low N contents. Nitrogen usually starts to be volatile at 200°C; therefore, N contents are low in most types of biochars. The high pH of biochar might be attributed to the high content of alkaline metals, i.e., Ca, Mg, and K, which are stable during biochar production. Despite the low nutrient content of biochar, its application to soils improves its fertility because it is usually added at high rates as soil amendments. The pyrolysis conditions play an important role for identifying the physical characteristics of biochar. The higher surface area of biochar is a consequence of high temperature during the pyrolysis reaction [25].

6. Applications of biochar for soil fertility improvement

As mentioned above the porous structure of biochar facilitates its adsorption of water and, therefore, increases soil water holding capacity [52, 53]. This might increase the efficiency of water use in the arid zone soils [54]. The previous studies also demonstrated that the addition of biochar increases both soil aggregation and saturated hydraulic conductivity but decreases soil bulk density [53, 55, 56]. Therefore, application of biochar is a recommended practice to improve the physical characteristics of light textured soils [3]. For soil chemical characteristics, most studies showed that biochar has a negative effect on the availability of soil nutrients, i.e., its application increases soil pH [57, 58]. The liming effect of biochar can be attributed to the high concentrations of cationic metals, i.e., Ca^{2+}, Mg^{2+}, and K^{+}, which are stable and do not volatilize during the pyrolysis process [25]. In most cases, biochar has a relative high pH (within the range of 8–11.5) [57, 59, 60]. Therefore, addition of biochar is more favorable for acidic soils than the alkaline ones. The black earth (terra preta) was an acidic soil in the enteral Amazon basin, and AL toxicity and P deficiency were the main reasons hindering the agricultural activities. Continuous applications of biochar to these soils neutralized soil acidity but increased the available P fraction; consequently, biochar enhanced and sustained soil health of terra preta [25, 32, 59]. Moreover, high doses of biochar can increase soil salinity [61–65]. On the other hand, the addition of biochar can raise soil organic matter contents and elevate soil cation exchange capacity (CEC) [66]. For nutrients contents, it is worth mentioning that most biochar types are typically low in nutrient contents, especially N. As a result, applications of biochar only in agricultural is not adequate to supply the needed macro- and micronutrients [25, 67]. However, biochar plays an important role in mitigating soil nutrient losses by seepage or leaching [66]. Applications of biochar to soils increased its OC contents, which is suitable for soil organisms and provides more favorable habitats to microbes and, therefore, facilitates soil biological activities [68]. In addition, the release of organic molecules suppresses the activities of soil microbes [69].

7. Limitation of biochar application in the Kingdom of Saudi Arabia soils

As mentioned above the high pH of biochar limited its applications in arid soils. For this concern, application of biochar to agricultural soils in the Kingdom of Saudi Arabia is very limited due to many reasons as follows:

1. Low cultivated areas in the Kingdom of Saudi Arabia: as mentioned above, agricultural activities in the Kingdom of Saudi Arabia are very limited due to the arid conditions.

2. The chemical characteristics of soils in the Kingdom of Saudi Arabia; especially soil pH is one of the major factors hindering the application of biochar to agricultural soils. Our demonstration proves that most types of biochar are of alkaline nature and its application to agricultural soil may negatively affect the availability of soil nutrients due to increasing soil pH. The pH of the produced biochar is a function of pyrolysis temperature and time; by elevating the pyrolysis temperature and time, the pH of the produced biochars increased to reach 11.5 in some studies [53].

3. The lack of knowledge regarding biochar technology and its beneficial role for enhancing agricultural activates.

In a bibliometric study conducted by Arfaoui et al. [70], they have shown that Iran, the Kingdom of Saudi Arabia, and Egypt are the highest contributor countries for biochar studies and publications in the Middle East countries. As shown in **Figure 2** (biochar article number and geographic distribution according to the

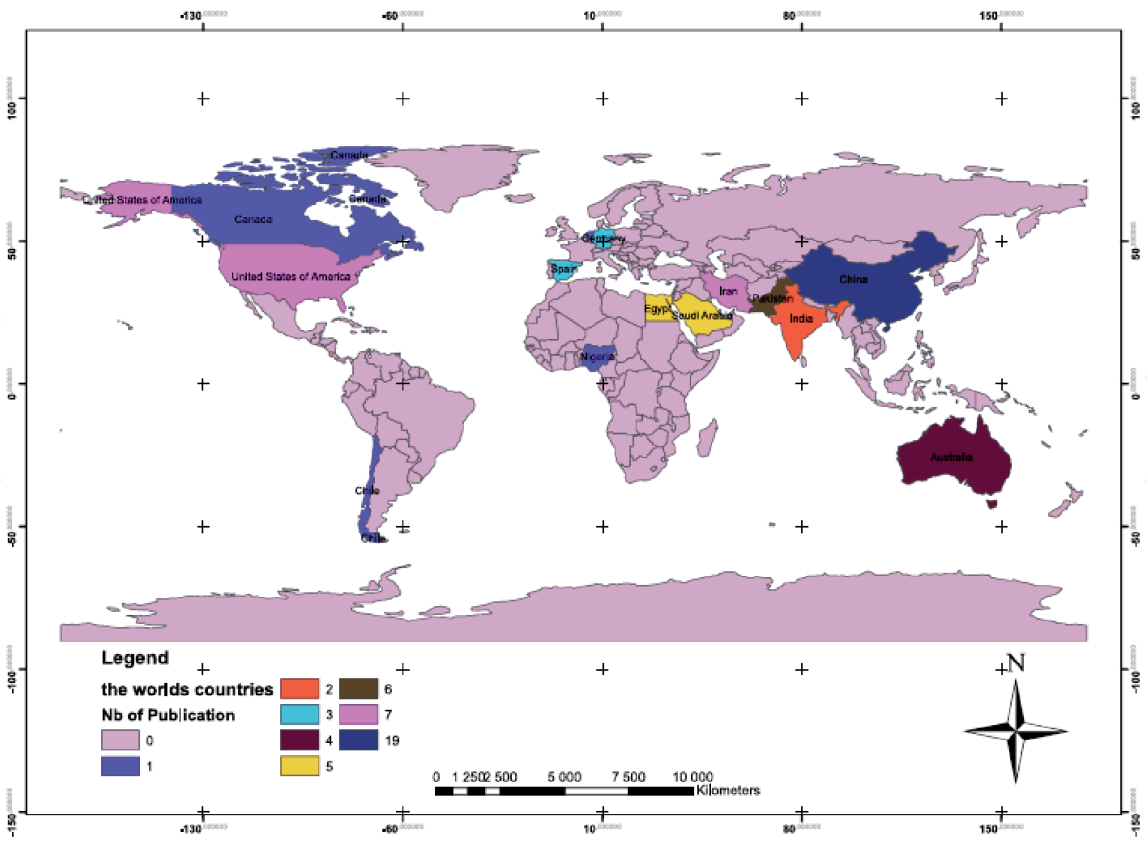

Figure 2.
Article number and geographic distribution according to the lead author's country of origin [70].

lead author's country of origin), China, the USA, and Iran are the leader countries for biochar studies and publications, followed by Pakistan, Middle East countries (Egypt and the Kingdom of Saudi Arabia), and to a lesser extent in Australia. In the Kingdom of Saudi Arabia, the Saudi Biochar Research Group in the King Saud University (Saudi Arabia) contributed to most publications in the Middle East countries.

We concluded that biochar is a promising soil amendment that can be used effectively for enhancing soil fertility. In arid regions like the Kingdom of Saudi Arabia, additional researches are needed to investigate the potential neutralization of biochar alkalinity; consequently, it can be added safely to agricultural soils. There are different sources of agricultural and food wastes that can be used for biochar production. In the case of date palm wastes, the average annual waste of one tree is about 40 kg; therefore, date palm wastes can be used effectively for biochar production in the Kingdom of Saudi Arabia. Therefore, the government of Kingdom of Saudi Arabia has to encourage the scientists for initiating intensive researches on biochar production and investigate its beneficial roles for improving soil fertility and agricultural production.

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